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Diagnostics of the technical condition of electric network equipment based on fuzzy expert estimates

Sergey Kokin[a], Vadim Manusov[b], Javod Ahyoev[c], Stepan Dmitriev[a,*], Alexander Tavlintsev[a], Murodbek Safaraliev[a]

[a] *Department of Automated Electrical Systems, Ural Federal University, Ekaterinburg, Russian Federation*
[b] *Department of Power Supply System, Novosibirsk State Technical University, Novosibirsk, Russian Federation*
[c] *Department of Power Electric Stations, Tajik Technical University, Dushanbe, Tajikistan,*

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Abstract

The paper describes a new possible method of diagnostics of the current technical condition of equipment using a mathematical model based on fuzzy expert estimates and the theory of fuzzy sets. The specifics of the task is determined mainly by the type of the obtained estimates, namely: causal relationships between the controlled parameters of the transformer equipment and defects that could entail their change and the possibility of further operation of the facility. At the same time, attention is paid to the problem of the degree of consistency of expert opinions that affects the quality of the assessment of the current technical condition of the studied object. The paper provides a comparative analysis of the arithmetic mean estimates and median estimates of the consistency of expert opinions. It is shown that the significant drawback of the arithmetic mean approach is its instability towards outliers of individual opinions moving the resulting value under the influence of the “dissident expert opinions”. On the other hand, the median estimate is free of such shortage; it is more outlier-resistant and simply discards a part of radically outlying expert opinions. For the first time, the Kemeny median has been used for technical diagnostics. Kemeny median is based on the introduction of a metric to the set of expert opinions, and axiomatic introduction of the distance between them. Also, the paper formulates a criterion on how to determine the optimal number of experts in the group.

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Keywords: Electric power; Electrical equipment of electric power systems; Technical diagnostics; Current state; Expert estimates; Degree of consistency; Coefficient of concordance; Kemeny median; Fuzzy causal relations; Fuzzy logic

1. Introduction

The development of electric power systems (EPS) and the increased requirements for the quality of their functioning depend to a large extent on the technical state of the electrical network equipment and the level of

* Corresponding author.
E-mail addresses: s.e.kokin@uruf.ru (S. Kokin), manusov36@mail.ru (V. Manusov), javod_66@mail.ru (J. Ahyoev), sa.dmitriev@urfu.ru (S. Dmitriev), a.s.tavlintsev@urfu.ru (A. Tavlintsev), murodbek.safaraliev@urfu.ru (M. Safaraliev).

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its operational activity. At present, the electrical equipment of electrical networks, substations, and power supply systems is quite worn out. This is because, in the process of real operation, the current technical condition of the electrical equipment is constantly deteriorating depending on the operating modes, and the impact of external conditions. This reduces the operational reliability of the system and increases the likelihood of failures. Along with this, the reliability of electrical equipment depends not only on the correct technical operation but also on the quality of the manufacture of electrical equipment, its maintenance, and timely repair, increased control of the technical condition, and assessment of the limit-state condition. In this regard, even higher requirements are being imposed on the operating personnel of various parts of technical systems and electrical equipment.

Building a system for assessing the current technical condition is a complex and vital task. The quality of functioning of modern electric power systems depends on the solution of this task. The complexity of modern electrical equipment and the variety of modes of its operation necessitates a revision of the existing traditional concepts of constructing diagnostic systems and the search for new solutions. One of the solutions proposed in this paper is the concept of combining traditional expert systems with artificial intelligence, namely, the theory of fuzzy sets and fuzzy logic. This inevitably establishes and enhances the role of the experts — specialists in specific narrow fields of technology.

The issue of the quality and concordance of expert assessments becomes even more vital due to the transition from the planned preventive repair approach based on maintenance at regular time intervals (PPR) to the operation of electric equipment based on the evaluation of its current technical condition (CTC), which provides for significant cost saving of 20%–30%.

Traditionally, technical tasks are solved utilizing engineering and metrological approaches and concerning operating requirements of electric equipment, but the growing complexity of the latter does not always allow a common specialist to make an unambiguous conclusion on the state of the electrical facility, for example, the conclusion on the condition of power transformer based on the readings of temperature sensors, gas chromatography, etc. Two solutions can be considered: the use of computer expert systems, or the collection and processing of expert opinions about the problem under consideration. However, the first of the two approaches can turn out to be useless in case the task is absolutely unique, while the second approach is more labor-consuming, but at the same time capable of producing a more substantial result.

This paper is focused on the second approach, namely the evaluation of current technical condition (CTC) based on mathematical methods of analysis and concordance of expert opinions. A new approach to the assessment of the current technical state presented in this paper involves a comparative analysis of the opinions of a group of experts based on the arithmetic mean estimates of their concordance and Kemeny median estimates, an approach previously used in some sociological research works. For the first time, the advantage of the median is shown as being less sensitive to individual "outliers" of opinions of the so-called dissident experts, which may be due to their excessive or insufficient competence. For the first time, a formula for the assessment of concordance of expert opinions based on the Kemeny median has been proposed

The main advantage, but also the constraint, of expert judgment in the evaluation of the current technical condition of electrical equipment, is the limited number of competent specialists who can act as experts in this particular field of expertise. The number of experts does not normally exceed 9–12 persons, which limits the applicability of statistical methods [1,2].

The key issue of expert assessments is their discordance. In the electricity sector, with its distinctive dualism of opinions of theoretic specialists and those specialists who operate in the field, the problem of concordance is especially acute. It may happen that as a result of expertise, the expert opinions will be divided into two major clusters. In this case, the analysis should be carried in each cluster separately.

2. Problem statement

The paper aims to analyze the concordance and search for a summarized expert opinion on the concrete example of evaluation of current technical condition (CTC) of power transformer, as well as to make recommendations on applying various methods depending on the situation, taking into account specifics of the task of technical analysis of possible electric equipment condition. In conclusion, we will formulate the criteria for determining the optimal number of experts.

As initial data for evaluation of current technical condition (CTC) of power transformer, we shall take expert opinions in a form of evaluations of fuzzy causal relations from 0 to 1, Table 1, that evaluate the probability of

Table 1. Example of cause-and-effect relations evaluation by one of experts.

Monitored parameters (Expert 1)	Defect in winding	Defect in isolation	Defect of core	Hot spots	Arcing	Gas bubbles	Mud in oil	System leakage
Moisture in oil	0	0	0	0.7	0	0	0	0.3
Gas in oil	0.1	0.5	0.1	0.3	0.7	0.3	0.2	0
Partial discharges	0.2	0.9	0	0	0.3	0.1	0.1	0
Temperature	0.8	0	0.1	0.5	0	0	0	0
Vibration	0.3	0	0.7	0	0	0	0	0
Oil breakdown voltage	0	0	0	0.5	0	0.2	0.7	0
Reheating	0.3	0	0.1	0.9	0	0	0	0

occurrence of a defect in the transformer equipment when the monitored parameters [3–7] deviate from the standard values.

We shall take 9 such tables, meaning there are 9 sets of opinions. One might notice that one complete table contains a lot of data that is inconvenient for analysis. For this reason, for the example, we will carry the analysis of the possible occurrence of defects concerning one parameter only, namely "Gases in Oil". This parameter has been selected because it contains the highest number of estimates for different types of defects, therefore providing for a more objective comparison of methods of analysis and concordance of expert estimates. All expert opinions per selected parameter are drawn together in Table 2.

Table 2. Experts' evaluation per "Gas in oil" parameter.

Gases in oil								
№ of expert	Defect in winding, a	Defect in isolation, b	Defect of core, c	Hot spots, d	Arcing, e	Gas bubbles, f	Mud in oil, g	System leakage, h
1	0.1	0.5	0.2	0.3	0.7	0.3	0.2	0
2	0.3	0.4	0.1	0.2	0.5	0.9	0.7	0
3	0.3	0.5	0	0.8	0.3	0.4	0.2	0
4	0.3	0.2	0.1	0.3	0.6	0.4	0.1	0
5	0.3	0.4	0.1	0.5	0.3	0.1	0.1	0
6	0.3	0.8	0.1	0.3	0.2	0.2	0.1	0
7	0.3	0.5	0	0	0.2	0.1	0.4	0
8	0.5	0.3	0.1	0.6	0.5	0.9	0.1	0
9	0.3	0.1	0.1	0.5	0.5	0.6	0.2	0

To simplify the analysis, we shall consider the evaluations to be equally distributed within the set of evaluations. The experts' competence will be also considered equal.

3. Concordance check

There are multiple ways to check concordance, major of them being described in [8]. Here we will use the concordance coefficient.

Before the calculation of the concordance coefficient, it is important to make a specific preparatory work [1]. That is, to represent all obtained expert estimates in one standard way so that the sums of all expert estimates will be equal to some number. The easiest way to do that is to replace fuzzy assessments by their ordinal rankings and to replace the assessments with the same ranking by the arithmetic mean of the two rankings of the corresponding assessments. The results of such transformations are shown in Table 3 (for convenience, the table is transposed).

Sum of ranks are calculated by using each factor, then arithmetic mean of ranks sum is calculated being equal to 40.5. Next thing d divergences are being sought out of arithmetic mean of sum ranks per each factor which can be shortly expressed with (1):

$$d = \sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n}\sum_{i=1}^{m} x_{ij}, \tag{1}$$

Table 3. Ranks matrix.

Factors/Experts	1	2	3	4	5	6	7	8	9	Sum of ranks	d	d^2
x_1	2	4	4.5	5.5	5.5	6.5	6	5.5	5	44.5	4	16
x_2	7	5	7	4	7	8	8	4	2.5	52.5	12	144
x_3	3.5	2	1.5	2.5	3	2.5	2	2.5	2.5	22	−18.5	342.25
x_4	5.5	3	8	5.5	8	6.5	2	7	6.5	52	11.5	132.25
x_5	8	6	4.5	8	5.5	4.5	5	5.5	6.5	53.5	13	169
x_6	5.5	8	6	7	3	4.5	4	8	8	54	13.5	182.25
x_7	3.5	7	3	2.5	3	2.5	7	2.5	4	35	−5.5	30.25
x_8	1	1	1.5	1	1	1	2	1	1	10.5	−30	900
Σ	36	36	36	36	36	36	36	36	36	324		1916

where m is a number of experts, n is a number of factors.

Next, we can proceed to the calculation of the concordance coefficient itself in accordance with (2):

$$W = \frac{S}{\frac{1}{12}m^2\left(n^3 - n\right) - m\sum T_i}, \tag{2}$$

where S is a sum of squad deviations of ranks sum from average sum and T_i is defined as

$$T_i = {}^1\!/_{12}\sum_{j=1}^{n}(t_j^3 - t_j) \tag{3}$$

where t_j is defined as the number of repeating elements in answers of i-expert.

By filling all known values in (2), we will finally obtain the concordance coefficient equal to $W = 0.58$.

As any statistical coefficient, concordance coefficient needs to be checked for the statistical significance, for example, using the criterion of chi-square. The 4th condition should be done:

$$m(n-1)W > \chi^2_{n-1,\alpha} \tag{4}$$

For the level of significance of $\alpha = 0.05$, we have a chi-square table value of 4.07, the statistical coefficient value being 36.54. It means that condition (4) is met! Thus, one can state that zero hypotheses of the absence of a statistic correlation between the sets of expert opinions can be rejected with a significance level of 0.05.

Nevertheless, the obtained value of the concordance coefficient shows an “average” level of concordance of expert opinions, which can affect the further comparison and choice of methods of finding a summarized opinion.

4. Arithmetical means and medians methods

Finding the arithmetical mean of some aggregate is a standard approach applied not only in expert methods but in technical analysis as well. Still, this method has a disadvantage of sensitivity to outliers, which can significantly move the arithmetical mean to the extent that it will no longer correspond to the intuitive perception of an arithmetical mean of the aggregate. The median estimate does not have this disadvantage, it is not outlier sensitive and is always defined as 0.5-quantile distribution, or value dividing the square under the curve into two equal parts, which is close to an intuitive perception of the arithmetical mean. In practice, both methods have their advantages and disadvantages. While the arithmetical mean moves under the influence of dissident expert opinions, which are not necessarily wrong (there is a chance that these particle experts are the most competent ones), the median method just cuts out part of the information which could be of value for the decision-maker (DM). In this regard, following the concept of stability [8], it is recommended to apply both assessments simultaneously to set apart the matching conclusions obtained by both methods. The results of processing the data from Table 2 are shown in Table 4.

Let us point out that parameters d and e turned to be less resistant, and the values of their arithmetical means and medians differ by nearly 0.1. This fact may lead to incorrect conclusions, such as that, for example, judging by the median assessment, parameter e is more significant than the others. The situation is complicated by the fact that usually, the number of experts is small, which makes it difficult to talk about statistical significance. Hence, getting back to the principle of stability, we will aim at enhancing the two methods with the third one that will serve as a control one. This time, we will turn to the algebraic methods.

Table 4. Processing results of expert evaluations.

Gas in oil	Defect in winding, a	Defect in insulation/isolation, b	Defect of core, c	Hot spots, d	Arcing, e	Gas bubbles, f	Mud in oil, g
Arithmetical mean, $M(x_j)$	0.3	0.411	0.089	0.389	0.422	0.433	0.233
Median	0.3	0.4	0.1	0.3	0.5	0.4	0.2

5. Kemeny's median

Application of the Kemeny median rule is based on the introduction of a metric into the sphere of expert opinions, and axiomatic introduction of the distance between the elements of the set of expert opinions. At the same time, it is important to know the exact set representing the opinions, because it affects the complexity of the task. In our case, it is convenient to convert initial expert opinions into pairwise comparisons, treating evaluations as ranks, and thus comparing them between each other for each factor. The example of such a matrix is presented in Table 5.

Table 5. Paired comparison matrix for the first expert.

	a	b	c	d	e	f	g	h
a	1	1	1	1	1	1	1	0
b	0	1	0	0	1	0	0	0
c	0	1	1	1	1	1	1	0
d	0	1	0	1	1	1	0	0
e	0	0	0	0	1	0	0	0
f	0	1	0	1	1	1	0	0
g	0	1	1	1	1	1	1	0
h	1	1	1	1	1	1	1	1

The matrix is filled according to the following rules:

- if $x < y$, then 1;
- if $x = y$, then 1;
- if $x > y$, then 0.

where x is a current index of line; y is a current index of column.

The total amount of pairwise comparison matrixes will be 9, according to the number of experts. Each pairwise comparison matrix represents an element of a P set of expert opinions. Alternatively, if we introduce the metric and put the elements of P set of expert opinions to the space of values, the elements will represent the points of this space. See the scheme (based on the example of 5 experts) in Fig. 1.

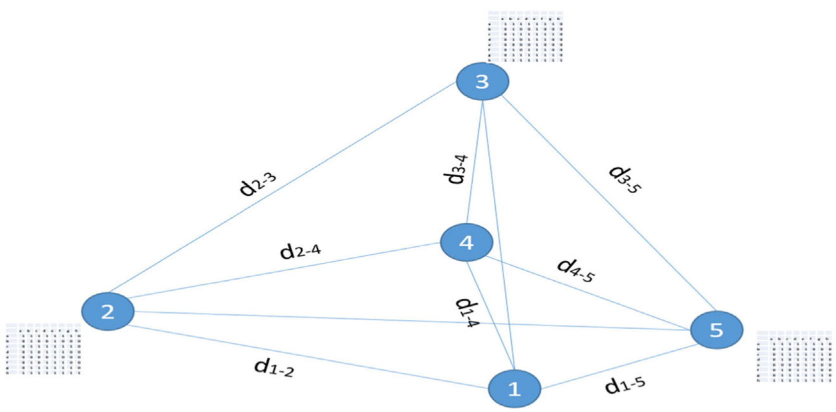

Fig. 1. Expert opinion space.

In other words, each matrix of pairwise comparisons is the point in the space of expert opinions [9,10]. The next step is the axiomatic introduction of the distance between the two points of this space - a sum of moduli of subtraction of all matrix elements occupying equivalent positions (5).

$$d(P_i, P_j) = \sum_{k=1}^{n} \sum_{l=1}^{n} \left| p_{i(k,l)} - p_{j(k,l)} \right| \tag{5}$$

where $p_{(k,l)}$ is the element of paired comparison, d is a Kemeny's distance.

Then, the Kemeny median can be defined as some element of P set that is less distanced from the rest of elements, which mathematically can be treated as minimal sum of distances from the fixed element of a P set to the rest of elements of this set:

$$M^*(P_1, \ldots, P_m) = arg\,min \sum_{i=1}^{m} d\,(P - P_i) \tag{6}$$

Representing the obtained distances in the form of a table, we will define the Kemedy median in accordance with (6) (see Table 6).

Table 6. Sums of Kemeny's distances from each expert's opinion including all the rest ones.

№ of expert	1	2	3	4	5	6	7	8	9
Sum of distances	129	157	107	115	129	114	184	121	126

The median turned out to be the opinion of expert No.3. By adding the set of evaluations of this expert to Table 4, we will obtain the results as shown in Table 7.

Table 7. Results of expert estimates processing based on Kemeny median.

Gas in oil	Defect in winding, a	Defect in isolation, b	Core defect, c	Hot spots, d	Arcing, e	Gas bubbles, f	Mud in oil, g
Arithmetical mean, $M(x_j)$	0.3	0.411	0.089	0.389	0.422	0.433	0.233
Median	0.3	0.4	0.1	0.3	0.5	0.4	0.2
Kemeny's median: №3 Expert opinion	0.3	0.5	0	0.8	0.3	0.4	0.2

Analyzing the results obtained in the table, it is a good time to recall the value of the concordance coefficient obtained above, namely W = 0.58. Based on this value, it is quite expectable that the assessments of the expert whose opinion became the Kemeny median will vary, sometimes strikingly, from the mean and the median values. This allows for the conclusion that the high degree of concordance (about $W \sim 0.7–0.9$ [11–15]) is a required condition for the feasibility of the application of the Kemeny median and other nonparametric algebraic methods.

6. Number of experts

To formulate the criterion for defining the maximum number of experts, let us use the results presented in Table 5. Based on the Kemeny distances obtained, it is clear that expert No.7 is a dissident expert, and his opinion significantly differs from the opinion of the other experts. Normally, the opinion of such an expert would be neglected during the analysis of evaluations, but as mentioned above, there is a possibility that this expert's opinion is the closest to the truth, while other experts' opinions combined are less close to it. In other words, there is a chance that the dissident's opinion is the most competent in the group.

Since the objective evaluation of the competence of each expert is an unattainable task (all we can count on is the subjective opinions of the other experts, or of this expert himself), it is the decision-maker (DM) who will have to make a judgment on excluding or not excluding the opinion of a given expert from the analysis [16]. Considering the case when the DM decides to exclude the expert's opinion, automatically, there will arise the possibility that the opinion of this very expert was the most relevant, and consequently, the whole analysis of all other opinions will go wrong.

Let us get back to the abovementioned example. To simplify the process, let us assume that all expert opinions are distributed equally, and all the level of competency of all experts is also the same. In such a case, the probability of obtaining the wrong analysis results will be $1/9 = 0.111$. Thus, we conclude that taking into consideration an equal level of competence of all experts, the expert No.7 will (supposedly, due to lack of detailed information) will have a 0.111 chance to "predict" a result that will be closer to the truth. Consequently, the remaining group of 8 experts has an $8/9 = 0.89$ chance that the area covering their opinions (hereinafter referred to as "working area") (see Fig. 2) will be closer to the truth than the opinion of the expert № 7.

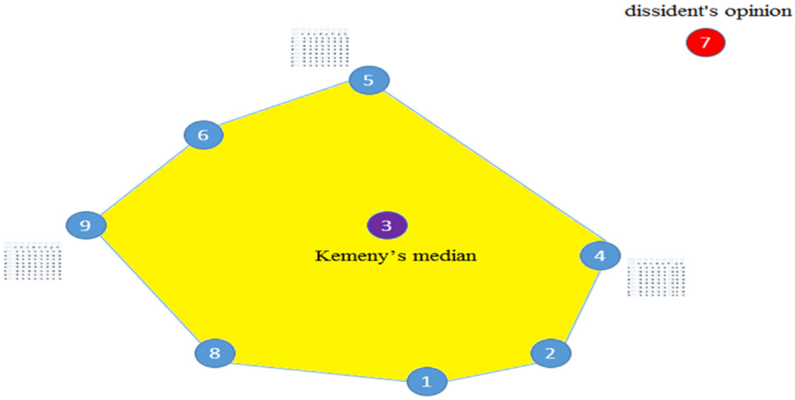

Fig. 2. Visualization of the space of expert opinions (working area highlighted yellow).

Taking the above into account, we will find out that with the increase of the number of experts in the working area, the probability of analyzed opinions being closer to the truth will also increase (providing that the number of dissident experts will not increase), and consequently, the Kemeny s median will become closer to the truth as well.

Now let us formulate the criterion. If before the expertise we assume that there will be no more than one dissident expert in the group, and define the desired probability of the working area being closer to the truth as α, then the number n of experts, whose opinions are distributed equally, and whose levels of competency are considered to be equal, should match the following:

$$(n-1)/n \geq \alpha \tag{7}$$

Thus, for example, if we define the desirable probability as $\alpha = 0.9$, the required number of experts n = 10.

7. Conclusion

The assessment of the current technical condition of electric network equipment and in particular, transformers requires not only non-destructive monitoring methods but also expert assessments. Such expert assessments can be regarded as some kind of preliminary diagnosis reflecting the experience and expertise of each technical expert. Expert assessments are supplementary logical and analytical estimates from the intuitive and heuristic points. Expert assessments rest on their subjectivity, which allows assigning varied subjective probabilities to causal relationships. This is because failures are rare and statistical sampling is insufficient for rigorous mathematical estimates. It was therefore necessary to build a new mathematical model based on the causal relationship between symptoms and causes of defects. In principle, the proposed method can be applied for technical diagnostics of any given electrical network equipment.

A comparative analysis of the consistency of expert opinions was carried out based on the arithmetic mean estimates and Kemeny median estimates. For the first time, a formula has been proposed to assess the consistency of expert opinions based on the Kemeny median. It has been shown that consistency can be regarded as acceptable if it equals $\alpha \geqslant 0.9$. Median estimates have been shown to have advantages because they are less sensitive to outliers of dissident opinions.

The attempt has been undertaken to formulate the criterion to determine optimal number of experts in a working group based on the assumption of equality experts opinions distribution, competencies equality as well as dissidents availability in a working group.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Orlov AI. Organizational and Economic Modeling: Textbook: In 3 Parts. Publishing House, Bauman Moscow State Technical University; 2009, p. 567.
[2] Gorsky VG, Orlov AI, Gritsenko AA. Method of matching clustered rankings. Autom Telemech 2000;(3):159–67.
[3] Manusov VZ, Ahyoev DS. Diagnosis of transformer electric equipment based on expert models with fuzzy logics. ELEKTRO. Elektrotek Elektroenergetika, Electrotekhn Promyshl 2015;(5):45–8.
[4] Manusov V, Ahyoev D. Technical diagnostics of electric equipment with the use of fuzzy logic models. In: Energy Systems, Materials and Designing in Mechanical Engineering. Applied Mechanics and Materials, vol. 792, 2015, p. 324–9. http://dx.doi.org/10.4028/www.scientific.net/AMM.792.324.
[5] Kofman A. Introduction into the theory of fuzzy sets: Translation from french - *M.:Radio i Svyaz*. 1982, p. 432, illustrations.
[6] Manusov VZ, Kovalenko DI. Fuzzy mathematical models of transformer equipment diagnosis. Nauchnyie Problemyi Trans Sib Dalnego Vostoka 2012;(2):254–7.
[7] Manusov VZ, Demidas JuM. Defect/fault statistics resulting in breakdown of power transformers. Nauchnyie Problemyi Trans Sib Dalnego Vostoka 2009;(1):405–7.
[8] Litvak BG. Expert information. Metodyi polucheniya and analiza. - *Radio i Svyaz*. 1982, p. 184.
[9] Kemeny J, Snell J. Cybernetic modeling: Some applications. - *Soviet Radio/Sovetskoye Radio*. 1972, p. 192.
[10] Secretaryov Yu. Production and Use of Heuristic Information While Taking Decisions: Teaching Manual. Novosibirsk: NSTU Publishing House; 2002, p. 36.
[11] Zotyev DB. By the definition of the problem of weight coefficients on the basis of expert assessments. Plant Lab Diagn Mater 2011;77(1):75–8.
[12] Novikov DA, Orlov AI. Expert assessments – tools for forecaster. Plant Lab Diagn Mater 2013;79(4):3–4.
[13] Khrustalyov SA, Orlov AI, Sharov VD. Mathematical methods of effectiveness assessments of managerial decisions. Plant Lab Diagn Mater 2013;79(11):67–72.
[14] Pugach OV. Mathematical methods of risks assessment. Plant Lab Diagn Mater 2013;79(7):64–9.
[15] Manusov VZ, Kryukov DO, Ahyoev DjS. Coordination of expert evaluations in the problem of current technical diagnostics of transformer equipment. In: Sovremennaya Tehnika I Technologii: Problemiy, Sostoyanie I Perspektiviy, Materialyi. YI Vserossiyskiaya Nauchno - Prakticheskaya Konferentsiya S Mezhdunarodnyim Uchastiem 24-25 Noyabrya 2016 G. Rubtsovsk: Posvyaschennaya 70-Letiyi Rubtsovskogo Indutrialnogo Instituta; 2016, p. 267–75.
[16] Petrovsky AB. Theory of Decision Making: Textbook for Students of Higher Education Facilities. Izdatelsky Centr Akademiya; 2009, p. 400.